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15. SUBJECT TERMS
remote sensing, ocean color, band sharpening, VIIRS, bio-optics, I-bands

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Improved monitoring of bio-optical processes in coastal and inland waters using high spatial resolution channels on SNPP-VIIRS sensor

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ABSTRACT

The dynamic and small-scale spatial variability of bio-optical processes that occurs in coastal regions and inland waters requires high resolution satellite ocean color feature detection. The Visual Infrared Imaging Radiometer Suite (VIIRS) currently utilizes five ocean color M-bands (410,443,486,551,671 nm) and two atmospheric correction M-bands in the near infrared (NIR; 745,862 nm) to produce ocean color products at a resolution of 750-m. VIIRS also has several high resolution (375-m) Imaging (I)-bands, including two bands centered at 640 nm and 865 nm. In this study, a spatially improved ocean color product is demonstrated by combining the 750-meter (M- channels) with the 375-m (I1-channel) to produce an image at a pseudo-resolution of 375-m. The new approach applies a dynamic wavelength-specific spatial ratio that is weighted as a function of the relationship between proximate I- and M-band variance at each pixel. This technique reduces sharpening artifacts by incorporating the native variability of the M-bands. In addition, this work examines the viability of replacing the M7-band (862 nm) with the I2-band (865 nm) to determine the atmospheric correction and aerosol optical depth at a higher resolution. These true (I-band) and pseudo (M-band) high resolution radiance values can subsequently be utilized as input parameters into various algorithms to yield high resolution optical products. The results show new capability for the VIIRS sensor for monitoring bio-optical processes in coastal waters.

Keywords: Remote sensing, ocean color, band sharpening, VIIRS, bio-optics, I-bands

1. INTRODUCTION

Characterizing and understanding the dynamics of coastal and inland optical water properties are central to multiple aspects of research oceanography, from fisheries to national defense. Traditionally, ocean color monitoring is used to characterize physical and biogeochemical processes occurring on global scales, however, the native resolution of many sensors is not sufficient for resolving coastal features. Spatial dynamics of coastal and inland regions are more variable compared to open ocean environments, given the additional influence of fluvial input, tidal activity, and wind-driven mixing. These optically complex waters are collectively known as "Case 2" waters[1], and require the use of multi-waveband algorithms as well as satellite sensors with improved spectral resolution and high signal-to-noise ratios (SNR).

The Suomi National Polar-orbiting Partnership (SNPP) satellite with the Visual Infrared Imaging Radiometer Suite (VIIRS), has 16 M-bands at a spatial resolution of 750-m at nadir, and five Imaging (I)-bands at a spatial resolution of 375-m at nadir. The locations and spectral response of the VIIRS visible/NIR channels are shown in Figure 1. The VIIRS is currently one of the most advanced sensors used for global monitoring of the land, ocean, and atmosphere. Currently, the deployed sensor on the SNPP satellite offers one pass on any given area in one day.

The primary goal of this study is to exploit the VIIRS higher resolution I-bands to resolve ocean features in coastal waters, and contribute to the further understanding of coastal dynamics. Improvements in the resolution of the ocean bands will allow ultimately for improved data validation as well as continued development of research applications with increasing degrees of confidence. An increased spatial scale may also enable the detection of important ocean features and processes that are inadequately resolved at lower resolutions.

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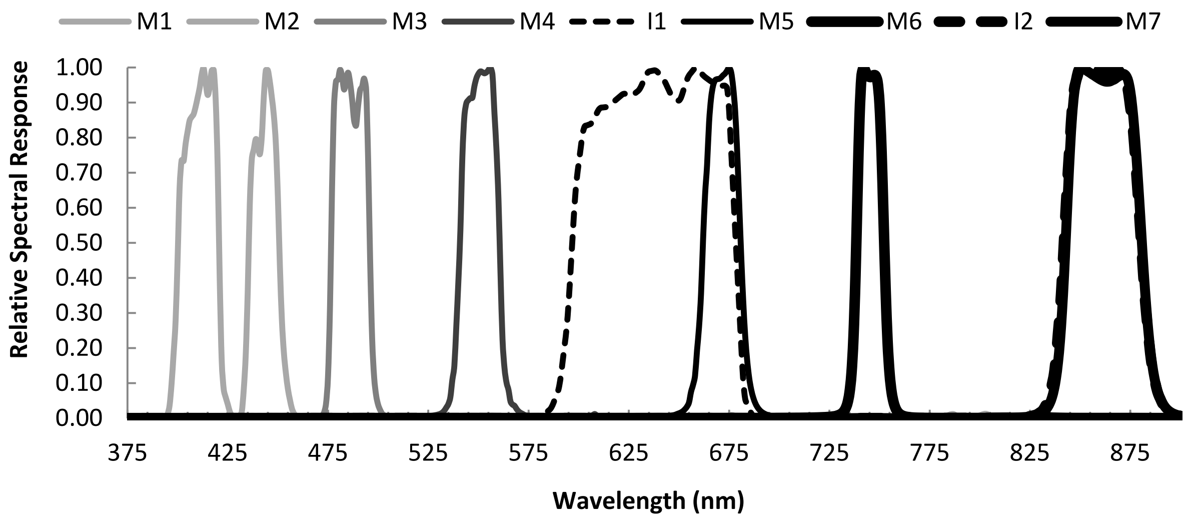

Fig. 1 The relative spectral response of the VIIRS Ocean Color/NIR channels. Bands M1-M7 are at a resolution of 750-m, while the I1 and I2-bands have a higher spatial resolution (375-m). Note the similar spectral response of the I2 and M7 bands.

2. SATELLITE PROCESSING

Level 1 VIIRS sensor data records (SDRs) were downloaded from NOAA's Comprehensive Large Array-data Stewardship System (CLASS, www.class.noaa.gov). All files were processed from SDRs (raw radiance + calibration) to Environmental Data Records (EDRs; geophysical parameters) using the Naval Research Laboratory's Automated Processing System (APS). The APS is an automated regional processing software tool used for research, development and analyses and also for operational product generation for Navy products. The APS uses the software package, n2gen, which is similar to the L2gen software used by NASA. The APS presently is capable of processing the M-bands of VIIRS to produce the 750-m bio-optical products, and also has the capability to process the five Imaging bands. The output of APS can be used by various image display software packages including SeaDAS (NASA) and ENVI (Exelis).

The scenes were processed using two atmospheric correction approaches. Sharpening techniques 1 and 2 (ST1, ST2; see Section 3) were processed using the standard Gordon/Wang[2] atmospheric correction at a resolution of 750-m, utilizing multi-scattering and iterative NIR correction[3]. One scene (ST3) was processed using the same atmospheric correction procedure, except the low resolution M7 band (862 nm) was replaced with the high resolution I2 band (865 nm). Standard flags were used to mask interference from land, clouds, sun glint, and other potential disturbances to the radiance signal. ENVI/IDL were used to perform the post-processing band-sharpening functions described below.

3. INCREASING THE RESOLUTION

3.1 Band Sharpening

The underlying principle of band sharpening involves the utilization of a high resolution image to interpolate information about spatial variability at other wavelengths. Many well established methods exist for utilizing broad panchromatic bands to sharpen multispectral data[4,5]. While the spectral bandwidth of the VIIRS I1-band is wider than that of the M-bands, it does not closely cover the full extent of the visible spectrum (Figure 1), therefore caution must be taken when interpolating outside of this spectral region. Previous attempts have been made to use a non-panchromatic high resolution channel to sharpen multiple lower resolution channels in the visible spectrum for producing true color imagery using the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor[6]. In this case, the procedure applied a static spatial resolution ratio obtained from a channel with similar spectral characteristics to the VIIRS I-band. We refer to this particular procedure as sharpening technique 1 (ST1).

The above sharpening technique works well for true color imagery, but has the potential to introduce some spectral artifacts, as it relies on the assumption that ocean color variability is spectrally independent. It is well know that each optically active constituent in natural waters imparts its own unique spectral signature based on differing absorption and scattering coefficients, as well as its relative abundance. For example, high concentrations of suspended particles increase the backscattering coefficient relative to the absorption coefficient, which will be amplified in the red regions of the spectrum (600 – 700 nm) where there is lower absorption by particles[7]. Meanwhile, wavelengths in the blue region of the spectrum, while also backscattered in the presence of suspended particles, are heavily influenced by *absorption* of phytoplankton cells, detrital material and chromomphoric dissolved organic matter (CDOM)[7]. Therefore, what variation is present in the red (I-band) region of the spectrum is not always translatable to the other visible channels, as these optical constituents affecting light return to the satellite are not strictly covariate.

Information regarding how each wavelength is related to one another may address this potential artifact and allow specific corrections to be applied to the spatial ratio approach. A comparison between the relative spatial variability present at each wavelength is a good quantitative indicator of where covariance and divergence in radiance patterns occur. Figure 2 demonstrates that, for a scene in the northern Gulf of Mexico from November 08, 2012, the spatial variability of red (640 nm) and blue (410 nm) radiance tends to exhibit similar patterns closer to shore, where optically active constituents from fluvial input are more likely to covary. Into the blue waters, however, the variance begins to diverge as absorption increases relative to backscattering. If this variability is resolved at each pixel, the spatial ratio may then be weighted as a direct function of variability for each wavelength. In practice, where the variability between the I-band and a particular M-band is similar at 750-m resolution, the assumption is made that the spatial distribution between these two bands is similar at 375-m resolution as well. Where divergence in variability occurs, the ratio may be adjusted in proportion to the difference in variance between the two bands.

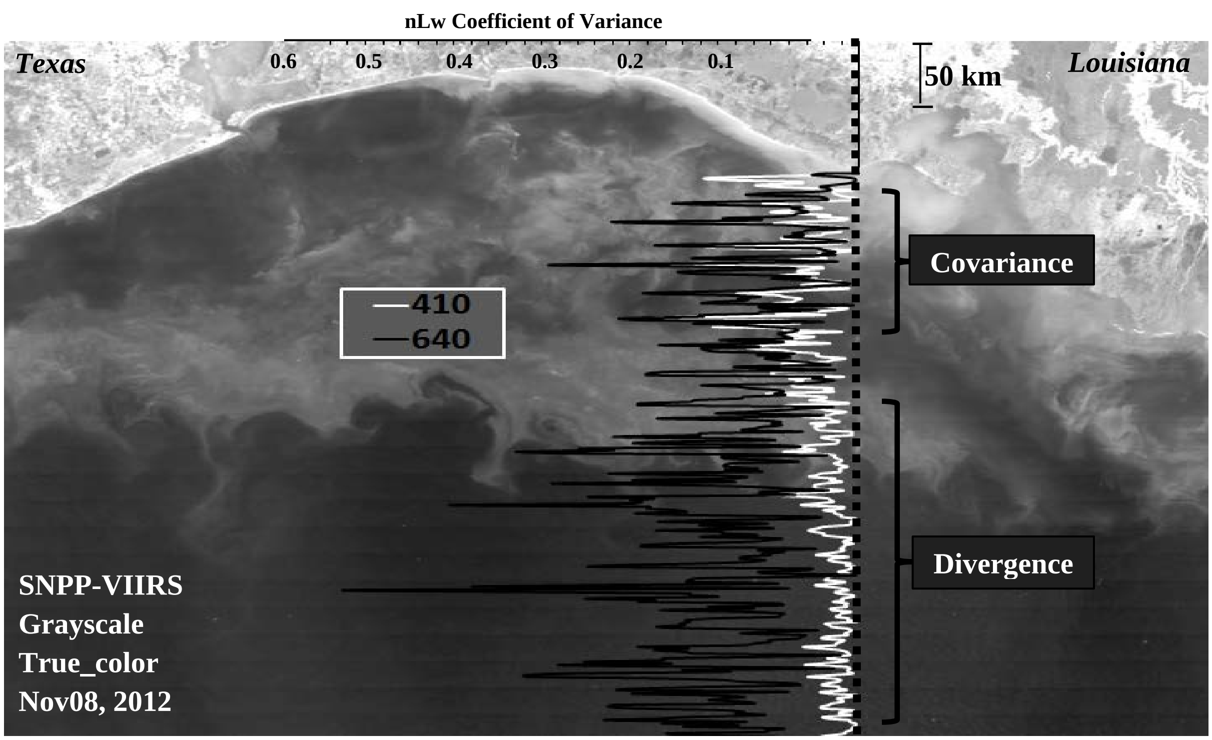

Fig. 2 The spectral separation of variability in an onshore/offshore transect. The Y-axis (dotted line) shows a profile of the normalized water leaving radiance (nLw) coefficient of variability (CV, SD/mean) at 410 nm (M1-band) and 640 nm, (I1-band) for surface waters in the northern Gulf of Mexico. The shown values represent the relative CV of a three-pixel moving average. A two pixel mean was obtained for both bands before performing statistical analysis to eliminate an upward bias of variability from the higher resolution band. Image: Grayscale true_color, northern Gulf of Mexico, November 08, 2012.

This approach involves computing a wavelength dependent spatial resolution ratio from the VIIRS I-band and the M-band that is to be sharpened. The adjusted spatial resolution ratio is computed at each pixel:

$$R(\lambda) = ([(I - I^*) \text{ x } (M(\lambda)_{CV} / I_{CV})_{\text{thresh}=1}] + I^*) / I^* \quad (1)$$

Where

$R(\lambda)$	Wavelength dependent spatial resolution ratio
I	VIIRS I1-Band at native resolution (375-m)
I*	VIIRS I1-Band at 750-m resolution (2 x 2 box average, pixels duplicated to 375-m projection)
$M(\lambda)_{CV}$	VIIRS M-Band coefficient of variance for 5 x 5 box (M-band bilinearly interpolated to 375-m)
I_{CV}	VIIRS I1-Band coefficient of variance for 5 x 5 box
$_{\text{thresh}=1}$	Ratio threshold, data[**WHERE**(data **GT 1**, /NULL)] = **1**

Here, the first step involves identifying how each I1-band pixel at full resolution (I) differs from the corresponding 2 x 2 I1-band average (I*). This is called the variability index, and represents the base value that will be manipulated for each wavelength. Next, the variability index is multiplied by the λ-dependent variance ratio computed at each pixel. This ratio is obtained by dividing the M-band coefficient of variance (CV; SD/mean of 5 x 5 box surrounding the pixel) by the I-band CV. The M-band is bilinearly interpolated to 375-m in order to eliminate the downward bias of variability that comes from averaging duplicated pixels. For best results, all ratio values > 1 are replaced with a value of 1 to prevent over sharpening in coastal regions. In addition, the land/atmfail values are converted to -NaN and eliminated from the calculation of mean and SD in order to preserve the resolution along the coastline. The product of the variability index and the λ-dependent variance ratio is called the λ-dependent weight. Next, the I1-band is re-sharpened by adding the λ-dependent weight to I*. Then, the adjusted spatial resolution ratio is computed by calculating the ratio of the re-sharpened I-band to I*, yielding R(λ).

Finally, the sharpened VIIRS M-band, $M_{375}(\lambda)$ is computed by:

$$M_{375}(\lambda) = R(\lambda) \text{ x } M(\lambda)^* \quad (2)$$

Where

$M(\lambda)^*$	VIIRS M-band (λ) at 750-m resolution, pixels duplicated to 375-m projection

This process is repeated for the full visible spectrum to create a “pseudo” 375-m product for each channel. This procedure is referred to as sharpening technique 2 (ST2). For this paper, the atmospherically corrected measure of normalized water leaving radiance (nLw) was examined in depth. This product (along with remote sensing reflectance, Rrs) is the base unit of many bio-optical algorithms, and may be utilized as an input parameter to yield higher resolution products.

3.2 Atmospheric correction

It is important to note that most ocean color algorithms are highly sensitive to inaccurate retrievals of nLw or Rrs. Approximately 90% of the signal observed at the top of the atmosphere (TOA) is due to atmospheric light scatter, including contributions from aerosols, Rayleigh scattering, ozone, and water vapor, and must be corrected for in order to interpret the signal from the ocean. While most of the atmospheric components have a known effect, information about the variable aerosol contribution and Rayleigh-aerosol interactions (L_a, L_{ra}) to the TOA reflectance (L_t) is derived from two near infrared (NIR) channels, where the contribution of radiance from ocean water is assumed to be negligible using the Gordon-Wang model. For VIIRS, the correction is currently being performed with the M6 (745 nm) and M7 (862 nm) bands, at 750-m resolution.

Figure 1 shows that that the high resolution I2 band spectral response is similar to the M7 band, and therefore may be a suitable replacement for higher resolution atmospheric correction. A similar approach was previously applied using the Moderate Imaging Spectroradiometer (MODIS) sensor[8]. However, the MODIS – Aqua 250 product had some issues with producing a noisy image product. This is partially the result of the inherent noise and out-of-band response of the 250m channels, which are not as well calibrated as the 1 km channels. Since the VIIRS I- and M- channels appear less noisy than MODIS – Aqua, the 375-m products from VIIRS would seem better suited than those from MODIS to help improve the resolution at the bottom of the atmosphere, but the atmospheric aerosol variability at 375-m did not improve the atmospheric correction process compared to the native aerosol variability at 750-m. This procedure is referred to as sharpening technique 3 (ST3).

4. RESULTS

The static band sharpening method (ST1), the λ-dependent band sharpening method (ST2), and the I2/M7-band atmospheric correction (ST3) were separately applied to enhance the visible nLw spectrum for a scene in the northern Gulf of Mexico from November 08, 2012. This image covers a wide variety of water types, including a high CDOM river plume, and heavy sediment loads close to shore. Figure 3 shows the original 750-m resolution image (Fig 3a) compared to the I-band enhanced atmospheric correction procedure (ST3; Fig 3b), and the pseudo 375-m resolution image of nLw at 410 nm (ST2, Fig 3c). The zoom (4x) window emphasizes an ocean front feature and demonstrates the advantages to the proposed band-sharpening methodology in coastal regions.

The use of the I2-band in atmospheric correction still produces noisy image products. This is possibly because the SNR in the I2-band is roughly half of that in the M7-band[9]. In this case, the channel's inherent noise may interfere with the very low radiance signal in the NIR. Data smoothing may offer some improvements, at the loss of resolution. Nevertheless, Table 1(ST3) shows that a scatter plot comparison reveals relatively small changes in the spectral quality. Table 1 offers additional evidence that it is imperative to use a wavelength-dependent weighting function when band sharpening. The first column of statistics (ST1) uses a non-weighted static spatial resolution ratio, as described by Gumley et al.[6] It is clear from the regression that the wavelengths further from the sharpening band are influenced negatively and to a greater degree than those closest to the I1-band. Visually, this introduces speckled data, especially in more blue waters, where the signal in the red is very low and the variability introduces an over-sharpening effect.

While the variability in the I1-band may be partly due to a low SNR, it is also important to note that changes in radiance detected from satellite imagery are not necessarily linear from pixel to pixel. That is, from a satellite perspective, while water relatively high in backscattering constituents may tend to exhibit more 2-dimensional characteristics as light is reflected from the surface of the ocean, factors of absorption are generally integrated with depth[10]. Since red light is absorbed much more quickly than blue light, it becomes necessary to account for this difference when using a red channel to sharpen a blue channel. The proposed methodology attempts to partially correct for this by assuming that the changes in spatial variance between multiple bands incorporate this non-linearity. At the very least, the tight correlation shown in Table 1 (ST2) show that the wavelength dependent sharpening technique does not introduce a substantial bias at any wavelength or change the radiometric quantities beyond reasonable values within a 750-m pixel.

Table 1. Scatter plot statistics comparing three different sharpening techniques to standard (750-m resolution, M7/M6 Gordon/Wang atm. correction) processing. ST1 – static spatial ratio as described by Gumley et al.[6]; ST2 – proposed λ-dependent spatial ratio; ST3 – I2/M7 band atmospheric correction.

	ST1		**ST2**		**ST3**	
	Equation	r^2	Equation	r^2	Equation	r^2
nLw_410	y = 0.7527x + 0.2702	0.7527	y = 0.9957x + 0.0048	0.9958	y = 1.0153x – 0.2425	0.9665
nLw_443	y = 0.7090x + 0.3277	0.7091	y = 0.9923x + 0.0088	0.9923	y = 1.0031x – 0.0108	0.9777
nLw_486	y = 0.7994x + 0.2394	0.7995	y = 0.9961x + 0.0082	0.9928	y = 0.9514x + 0.0477	0.9809
nLw_551	y = 0.9772x + 0.0150	0.9769	y = 0.9972x + 0.0020	0.9967	y = 0.9725x + 0.0062	0.9976
nLw_671	y = 0.9969x + 0.0003	0.9960	y = 0.9987x + 0.0002	0.9977	y = 0.9733x – 0.0097	0.9904

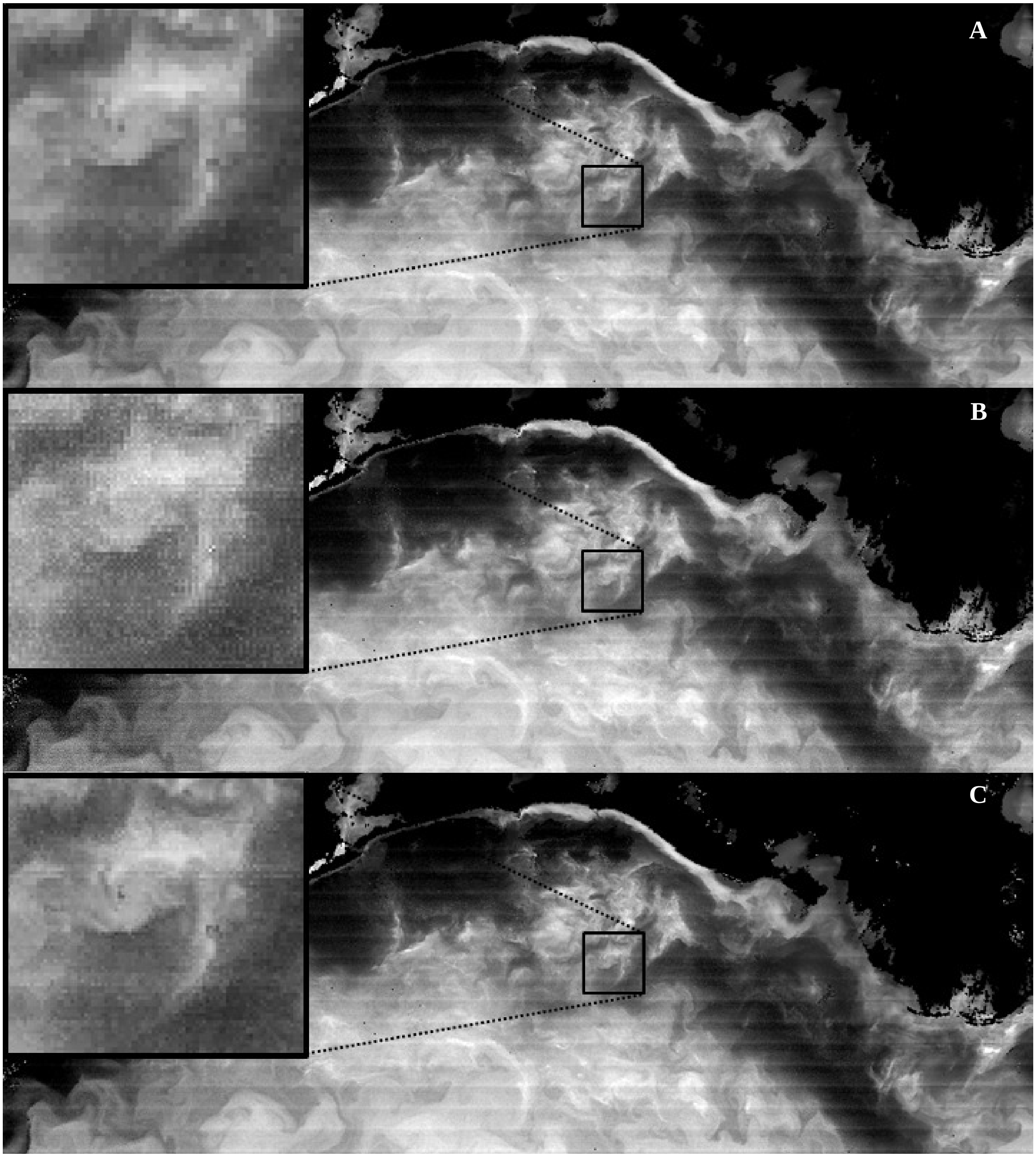

Fig. 3 Comparison of VIIRS (A) nLw_410 at standard 750-m resolution with M7/M6 atm. correction, (B) standard 750-m resolution with I2/M7 atmospheric correction, and (C) pseudo 375-m resolution with M7/M6 atm. correction. A marked increase in detail is shown in the pseudo 375-m resolution image, helping resolve ocean fronts and other optical boundaries in highly dynamic regions. The enhanced atmospheric correction procedure yields a noisy image, in spite of the similar spectral response between the M and I-channels at this wavelength. Image: northern Gulf of Mexico, November 08, 2012.

The weight applied changes not only as a function of wavelength, but also the water type, and the specific band response in that water type. Figure 4a shows the visible nLw spectrum for various regions of interest (ROI; 25 x 25 box mean and SD), from a bay to blue water (see Figure 5 for locations of ROI), illustrating the diversity of water types in coastal waters. The bottom figure shows the spectrum of the mean λ-dependent variance ratio (see Eq. 1) for various regions. In essence, the higher the ratio, the higher the I1-band weight that was applied to the sharpening. This plot shows that the red channel has the highest I1-band weight applied in all regions. This is to be expected since the I1-band (640 nm) is spectrally similar to the M5-band (671 nm). The decline in weight moving into the blue water is possibly a result of the increased SNR in the I1-band in this region. The blue channels are weighted lower in the offshore regions, but retain some patterns of I1-band variance in the bay and coastal regions, likely as a result of the covariant distribution of CDOM and suspended particulate matter. Variance in M4-band (551 nm) is less relative to other bands in the bay and coastal region, as the optical signature of variable biogeochemistry in these regions affects the red and blue wavelengths more.

Given the extremely variable distribution of optically active constituents in the water, it is useful to look beyond arbitrary ROIs. Figure 5 visually illustrates where the weights are being applied more/less as a function of variability relative to the I1-band. This figure shows that the greatest amount of sharpening occurs at ocean boundary regions, and varies considerably for different wavelengths. Even though there is less blue radiance closer to shore as a result of high CDOM absorption, the I-band sharpening weight is increased at 410 nm (Figure 5a) due to presumed covariance with red backscattering (suspended particles). Figure 5b also shows that the M4-band tends to covary with the I1-band in the offshore river plume, presumably rich in CDOM. The ratio of red to green reflectance has been found to show a robust correlation with estimates of CDOM in coastal[11] and lake[12] waters, therefore this covariance is expected in this region.

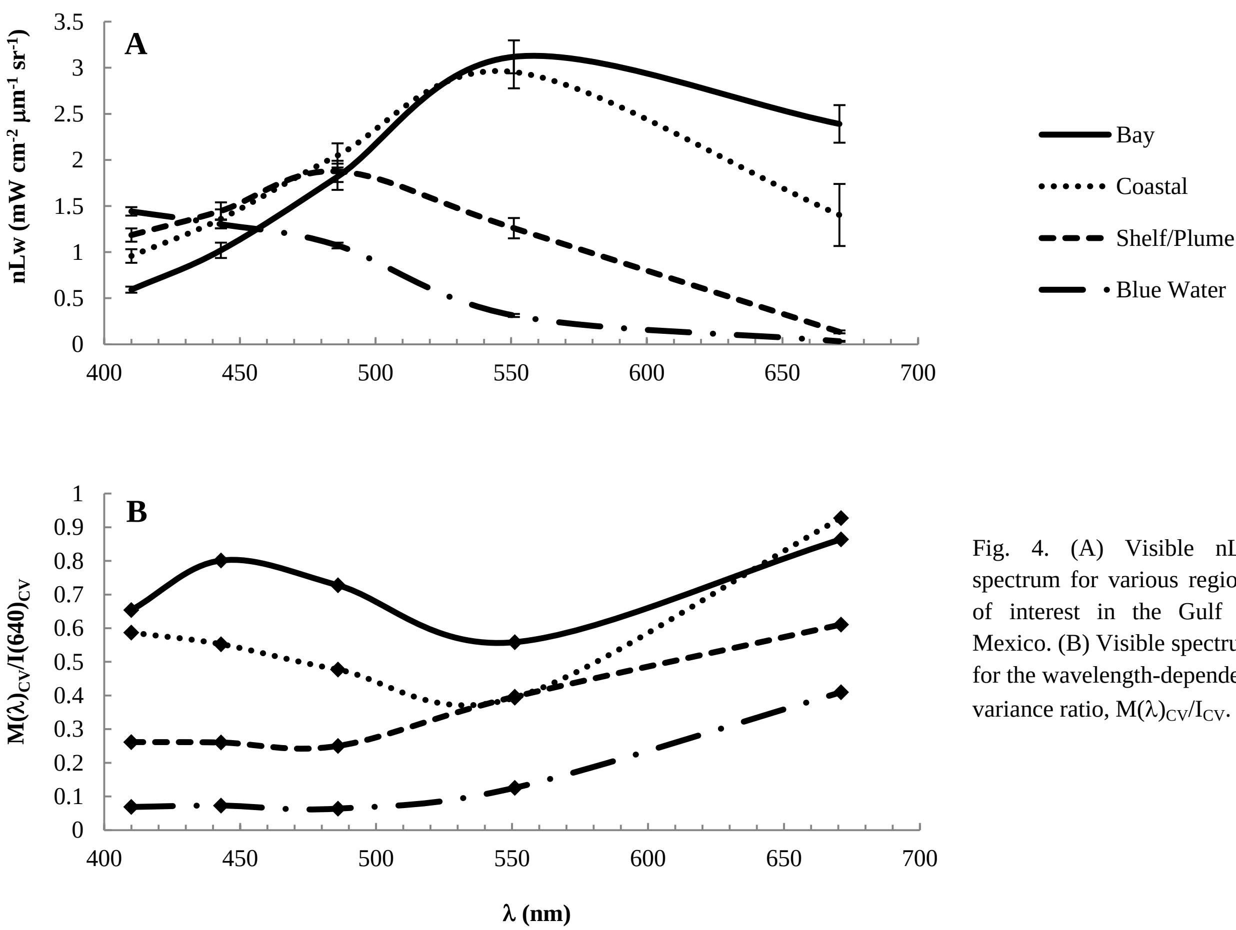

Fig. 4. (A) Visible nLw spectrum for various regions of interest in the Gulf of Mexico. (B) Visible spectrum for the wavelength-dependent variance ratio, $M(\lambda)_{CV}/I_{CV}$.

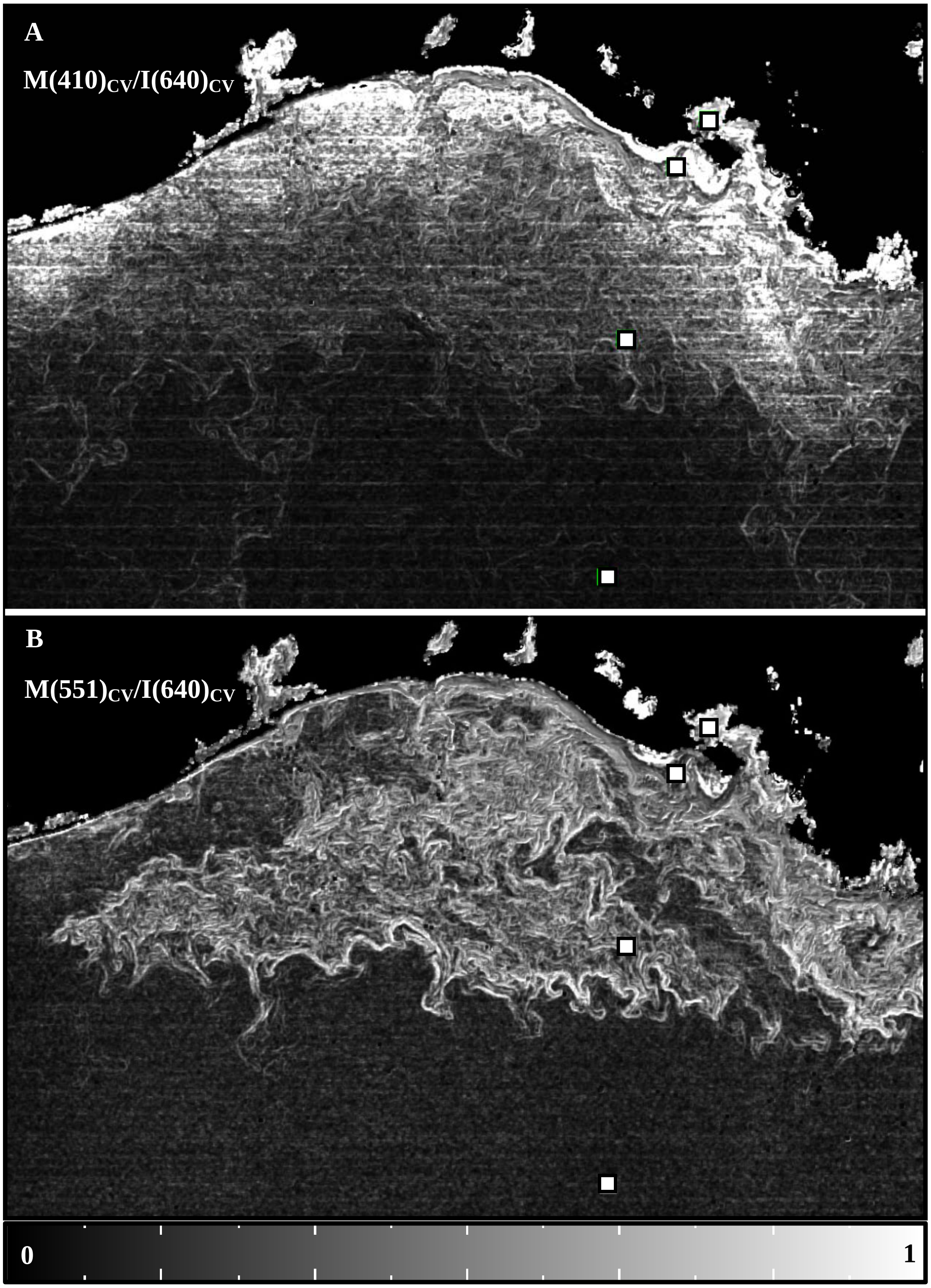

Fig. 5. Image of the λ-dependent variance ratio for the M1-band (A; 410 nm) and the M4-band (B; 551 nm). The lighter regions show areas where the I1-band weight was applied higher relative to the darker regions. Notice that the weight is applied heavier within the river plume boundary region for the M4-band while the coastal regions are weighted heavier in the M1-band. The white boxes show the locations of the ROIs in shown in figure 4.

However, where sharpening techniques tend to come under criticism is not where the high and low resolution bands covary, but where they diverge. While illustrating the similarities between the bands, Figure 5 also shows that there are vast differences. As previously mentioned, the optical properties of the water often do not change in similar ways, and the difference may be non-linear. The proposed methodology attempts to self-regulate the introduction of artifacts by reducing the weight as variance between bands is increased. For instance, a 10-fold decrease in the M-band variance relative to the I-band variance would lead to 1/10 of the original I-band weight to be applied, and the original M-band value is not changed substantially.

5. CONCLUSIONS

A procedure for the spatial enhancement of ocean color products in dynamic and optically complex waters is proposed using a sharpened visible radiance spectrum for VIIRS. This methodology utilizes the I1-band (640 nm, 375-m resolution) as the basis for sharpening, but modifies the weight of this adjustment based on the relative variability between the I- and visible ocean M-band for each pixel. The results show a marked increase in resolution for the visible nLw spectrum. Enhancement of the atmospheric correction was also attempted by replacing the lower resolution M7-band (750-m) with the higher resolution I2-band (375-m), both centered near 865 nm. The I2-band substitution produced noisy imagery, possibly as a result of the low SNR. While the I1-band also has a relatively low SNR, the increased ocean signal relative to the NIR, in conjunction with a λ-dependent spatial weighting function, reduces noisy imagery in the band-sharpening process. Further statistical and visual analysis shows that the proposed sharpening technique does not introduce a substantial bias to radiometric quantities, and varies substantially between wavelengths. The reliability of the method is due to the self-regulating nature of the algorithm, which prevents the over-application of the high resolution channel. The behavior of these sharpened images in bio-optical algorithms is currently under investigation.

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